Parallel Transmission- Methods, Hardware and Applications

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<u>Introduction</u>

Over the last few years, the field of parallel imaging has revolutionized the field of rapid MR imaging. The basic idea of parallel imaging is to use multiple receive coils to partially encode the received signal, thereby allowing faster imaging [1-16]. This in turn has led to a near explosion of receiver subsystem technology, with systems of up to 96 channels already in the field [17].

In this lecture we will discuss the application of these concepts to RF transmission, referred to here as parallel transmission. The basic idea of using multiple transmit ports has been around for several years. The first proposals focused on using optimized magnitude and phases for different drive ports on a volume coil to achieve a controlled or homogeneous excitation profile [18-19]. More recently, the application of parallel transmission to multidimensional RF pulses has been proposed [20]. While the most common use of these pulses is to excite a localized region for uses such a motion navigators [e.g. 21], these pulses have also been proposed as a way to compensate for almost every significant problem in high field imaging, such as B1-inhomogeinety.

We begin with a simple mathematical description of the problem. If we assume we have a coil with a homogeneous B1 field, the excited profile can be described (omitting multiplicative constants for simplicity) as:

$$M_{excite}(\vec{x}) = \int B_1(t) e^{i\vec{k}(t)\vec{x}} dt \qquad [1]$$

where $M_{excite}(\vec{x})$ is the 3D excited spatial profile resulting from the application of an RF pulse defined by $B_1(t)$ applied during a gradient defined by

$$\vec{k}(t) = -\gamma \int \vec{G}(t) dt \qquad [2]$$

where $\vec{G}(t)$ is the gradient field (in vector form) as a function of time. $\vec{k}(t)$ is the resulting harmonic modulation and $\vec{x}$ is the 3D spatial coordinate. This is analogous to the imaging problem, wherein the object is given by the Fourier transform of the received signal:

$$M(\vec{x}) = \int S(t) e^{i\vec{k}(t)\vec{x}} dt \qquad [3]$$

where in this case, $S(t)$ is the received MR signal.

The focus of this talk is to investigate all forms of multiport or parallel excitation strategies. In this case, we envision a setup where one effectively has an array of multiple coils, each with a unique sensitivity pattern (which could be separate meshes or modes of a birdcage, for example), instead of a single homogeneous coil for excitation. In general, we desire to use these different coils or meshes in unison to excite a particular pattern in the object. In this case, the excited pattern is given by the linear combination of the sensitivity weighted waveforms:

$$M_{excite}(\vec{x}) = \int \sum_{l=1}^{L} C_l(\vec{x}) B_{1,l}(t) e^{i\vec{k}(t)\vec{x}} dt \quad [4]$$

where $C_l(\vec{x})$ is the sensitivity of coil l where $l = 1...L$ for L coils. In this case, the determination of the required B_1 fields for a given excitation pattern are made much more complex, since they are now intrinsically linked to the spatial profiles of the individual coils. To date, there have been many approaches used to determine the desired pulses.

General Multiport (Array) Excitation

In this most general case, the B_1 fields of the various coils can vary independently in time in each coil. However, as will be discussed later, this requires extensive hardware modification to implement, which has been unavailable until just a few years ago. For this reason, many groups have previously focused on using fixed analog networks, normally to generate a homogeneous excitation at high frequencies. These networks can be set up to provide a fixed magnitude variation, a fixed phase variation or both to each coil or mesh in the array [19]. This can be described by

$$M_{excite}(\vec{x}) = \int \sum_{l=1}^{L} n_l C_l(\vec{x}) B_1(t) e^{i\vec{k}(t)\vec{x}} dt \quad [5]$$

where n_l is the weighting factor for a given coil in the array, which is fixed in time. In this case, the same B_1 is transmitted in each channel of the array. One can implement a scheme such as this by varying capacitors on different meshes of a birdcage coil to control the relative currents in the different meshes [e.g. 18,19], or by using external feed networks [e.g. 22]. As expected, systems which can vary both the phase and magnitude of these weighting factors perform better than those with fixed values, even though a fixed network can provide gains compared to a normal 2-port feed birdcage or TEM setup. In addition, as expected, those setups with more independent coils or meshes perform better than those with fewer elements [19].

Time Varying Array Excitation

However, as shown initially by Katscher et al [20], these schemes do not exploit all of the available degrees of freedom. In their seminal work, they proposed using different time varying B_1 pulses in each coil of the array to excite a multidimensional profile in a reduced time. This idea, dubbed Transmit SENSE, is based on the parallel imaging method SENSE [8]. As in the parallel imaging method, a portion of the k-space trajectory of the RF pulse is skipped, which would normally result in an aliased excitation pattern. However, by using different pulses in each coil of the array, the aliasing can be canceled in the superposition of the different coil patterns. Since its initial presentation, this basic idea has been successfully implemented by several groups [e.g. 23-24, plus a multitude of abstracts from last year's ISMRM].

The primary problem in this method is the determination of the RF pulses to be excited in each coil of the array. While several methods have been proposed [20,23,25-27], the basic idea of all is based on solving a system of equations given by Equation 5 above for each location in the excitation space. This is very similar to the generalized SENSE formulation used for non-Cartesian trajectories [11]. These will be discussed in detail during the talk. Another problem in methods such as this is the exact determination of the coil sensitivities for use in the design of the RF pulses.

Another option which can potentially avoid this problem is to use a k-space based formulation [27]. In this case, as in the parallel imaging situation, the k-space trajectory is broken up into several subsets. For example, a Cartesian EPI-like trajectory can be broken up into even and odd lines. The total RF pulse can then be viewed as the sum of the pulses on these trajectories:

$$RF_{Total} = RF_{Even} + RF_{Odd} \qquad [6]$$

where RF_{Even} and RF_{Odd} correspond to the various segments which make up the complete multidimensional RF pulse. As in k-space parallel imaging method, we can express all of the segments in terms of just one of them, in this case the even trajectory:

$$RF_{Total} = RF_{Even} + \sum_{l=1}^{L} n_l RF_{Even} \qquad [7]$$

where n_l gives the weights for this transformation. As in the parallel imaging situation, one can use an autocalibrated approach, wherein the RF_{Even} and RF_{Odd} portions are separately excited and fit to one another to determine the correct weighting factors, thereby avoiding the need for quantitative coil sensitivity maps. Again, more detailed descriptions of this method will be given during the lecture.

Hardware Requirements

The actual implementation of these modern parallel transmit concepts such as these requires significant hardware modification compared to the normal set up. One of the most significant changes is the requirement of separately controlled transmitters for each channel in the array. High power transmitters are in general very expensive, and this cost has been one of the primary hindrances to the widespread application of these ideas. Another significant limitation is the need for coil with independent sensitivities in the array. This is normally achieved in receive-only arrays by using preamplifiers with a high input impedance to block currents on the coil elements, thereby increasing their isolation. This is not possible during transmission, so alternative methods for decoupling of the coil is needed. A very interesting potential solution to both of these problems was proposed by Kurpad et al [28]. Their basic idea is effectively to move small transmitters onto each coil element of the array. In this way, one can generate a high impedance setup on the coil elements, which essentially mimics the preamplifier in a receive array. An additional 15 dB of isolation has been obtained to date. The most significant limitation in this type of setup is the relatively low power that can be generated on each element. However, as the number of elements increases, this will become less and less of a problem.

Potential Applications and Limitations

The potential application of these concepts are nearly endless. Besides shortening simple multidimensional pulses, the most immediate application, which could have significant application, is improving the excitation homogeneity at very high fields. This is sometimes referred to as B1-shimming. Significant improvements in excitation homogeneity have already been observed [e.g. 24].

Besides the hardware limitations, another area which has yet to be fully explored is the impact on SAR. While some initial simulation-based studies have shown relatively benign SAR performance [e.g. 29], the development of a full SAR monitoring system is still needed. This will be particularly challenging at high fields, where the observable B1 fields and the local heat-inducing electric fields are potentially spatially separated.

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